The Field Project CLEOPATRA, May–July 1992 in Southern Germany

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Abstract

CLEOPATRA (Cloud Experiment Oberpfaffenhofen and Transports) is described. This field program was performed in southern Germany 50 km north of the Alpine foothills, an area of known enhanced thunderstorm activity. The general goal is to quantify elements of the hydrological cycle on a regional scale in dependence upon precipitation events and the vegetation state. Embedded goals are to describe the mechanisms that force organizations of deep convective systems, to compare theories and observations of atmospheric depositions, and to test and compare observational methods from ground, aircraft, and space. The observational setup, including 10 research aircraft, four radar systems, and different ground-based networks, was operational from 11 May until 31 July 1992 to cover an essential period of the growing season.

1. Introduction

Steps implementing the Global Energy and Water Cycle Experiment (GEWEX) were discussed by the Joint Scientific Committee of the World Climate Research Programme recently. One conclusion was that multiregion cloud system studies are needed in order to provide a basis for improvement of the representation of cloud and precipitation processes in larger-scale atmospheric models. It was affirmed that "better knowledge is needed of the mesoscale phenomena responsible for heavier rainfall as well as of other important dynamical processes such as transports of heat, moisture and momentum in convective clouds and slantwise ascent, interaction of clouds with boundary layer fluxes, cloud–radiation feedback, and orographic forcing" (WMO 1991).

Programs combining observation and modeling studies were suggested, and a two-part approach considered: 1) a mesoscale subprogram; 2) a "cloud-scale subprogram based on very fine mesh numerical models with a 1-km grid (covering a domain of 10 000 km^2), and intensive observations of cloud system dynamics and microphysics from aircraft (with Doppler radar, radiometers and in situ probes) supplemented by surface-based facilities (radars, etc.) in order to develop archetypal cloud models of convective systems in low and high latitudes, over oceans and continents" (WMO 1991).

DLR (Deutsche Forschungsanstalt für Luft- und Raumfahrt), together with groups from different universities and other research organizations, planned the Cloud Experiment Oberpfaffenhofen and Transports (CLEOPATRA), conducted during summer 1992 in southern Germany. DLR is the German aerospace research establishment. One of its research centers is located near Oberpfaffenhofen about 25 km west of Munich. This site, about 50 km north of the Alpine foothills, formed the center of the experiment. The area north of the Alps is known to have enhanced thunderstorm activity.

The goal of this field project was to quantify elements of the hydrological cycle on a regional scale. The water exchange among soil, vegetation, and atmosphere was to be investigated in dependence on precipitation events and vegetation status over the growing season. This field effort for the first time tackled both urgent objectives—deep convection and water exchange with the biosphere—in a well-coordinated and interdisciplinary approach. Mass and momentum transports by deep convection as well as the precipitation formation itself were topics of interest; the understanding of the formation of broken boundary-layer cloudiness also needs further investigation. Moreover, trace gas transports and scavenging by clouds and precipitation should be investigated for selected situations. Last but not least, the experiment offered an opportunity for comparing different remote-sensing methods with in situ and ground truth measurements and quantifying the impact of weather elements on satellite communication links.

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2. Objectives

a. A more quantitative description of deep convective systems in southern Germany, their formation and organization in dependence on synoptic conditions, the associated vertical mass transports, the precipitation formation process, and interactions with the environment

Three-dimensional numerical studies of convective storms have shown that some basic dynamical mechanisms determining storm type can be explained in terms of environmental stability and wind shear (Weisman and Klemp 1982). It could be shown that a Richardson number formulation was able to distinguish between supercells and multicell storms.

The proposed single cell–multicell–supercell categories probably mark arbitrary points on a more or less continuous scale of thunderstorm types. The feeder-cell mechanism and the graupel process as dynamical and microphysical mechanisms for hail embryo growth were found to be essential for precipitation formation in multicell hailstorms. But, according to the different types of storms, hail embryos may grow in different locations in the cloud.

Radar and satellite observations show that thunderstorms often are organized on the larger mesoscale and occur in cluster or linelike formations. Here, boundary-layer or other types of forcing, like waves, orography, local heat sources, or convergence lines, can be important (Meischner et al. 1991).

Observations have shown that gravity waves that were excited elsewhere might travel over distances on the order of several hundred kilometers without significant dissipation. If the associated vertical lifting of air masses is strong enough to release convective instability, thunderstorms might be initiated. This trigger mechanism is usually related to wavelengths of 50 km or more (Koch and Golus 1988). Shallow convection excites gravity waves (referred to as convection waves) with typical wavelength of 10–15 km (Hauf and Clark 1989). They might also trigger deep convection. On the other hand, thunderstorms themselves initiate gravity waves in the troposphere.

The hypotheses investigated were:

- Unstable stratification up to altitudes well above 10 km and strong wind aloft favor supercell formation.
- Unstable stratification up to about 8 km altitude and strong wind up to that height favor multicell thunderstorms.
- Unstable stratification up to about 8 km altitude, moderate wind aloft, and strong wind shear near ground favor squall-line formation.
- Thunderstorms generate gravity waves, and gravity waves may trigger thunderstorms.
- Mass and energy transports to the upper atmosphere can be estimated for different storm types.
- Heavy precipitation is formed via graupel acting as hail embryos.

b. Understanding transports, modifications of air pollutants, and their scavenging by clouds

The removal of pollutants from the atmosphere is intimately linked to the development of clouds and precipitation. As clouds and precipitation are the result of a close interplay between microphysical and dynamical processes, the scavenging of gases and aerosol particles also is intimately dependent on these processes. The essential microphysical processes that control the uptake of particulate and gaseous pollutants are nucleus scavenging, impaction scavenging, and gas diffusion.

Calculations with cloud models performed so far suggest testing by field experiments the following hypotheses (Flossmann 1991; Flossmann and Pruppacher 1988; Ahr et al. 1989; Flossmann et al. 1985, 1987):

- The scavenging efficiency of a cloud for aerosol particles and pollutant gases is closely related to its precipitation efficiency.
- Nucleation scavenging is the most effective mechanism to take up particles.
- Below-cloud scavenging contributes only a small percentage to the total aerosol scavenging by clouds and precipitation.
- The aerosol and gas mass scavenged by clouds is redistributed inside the cloud water such that the main aerosol and gas mass is always associated with the main water (or ice) mass.
- In deep convective precipitating cold clouds, graupel plays an essential role in particle and pollutant gas scavenging.
- Nucleation scavenging of aerosol particles produces a rather sharp cutoff in the aerosol size distribution of the cloud interstitial aerosol inside the cloud.
- The water-insoluble portion of the mixed aerosol particle substantially affects the scavenging capacity of clouds (Schütz and Krämer 1987; Krämer and Schütz 1988; Ahr et al. 1989).

c. Determination of the conditions for the formation of broken stratocumulus cloud layers at the top of the boundary layer

The properties of the boundary layer vary considerably when an initially solid stratus layer at top of the convective boundary layer breaks up into a broken stratocumulus layer. In particular, a broken cloud layer differs from a solid cloud layer in the radiation and entrainment properties. Over land, a cloudy layer often gets quickly dissipated once the cloud layer breaks up.

In recent years, several investigations considered the cloud-top entrainment process. It has been suggested that the cloud-top entrainment instability (CTEI) condition decides the transition from a solid to a broken layer. The classical CTEI condition is formulated as a jump condition in the equivalent potential temperature and total water content (Deardorff 1980; Randall 1980; Kuo and Schubert 1988; MacVean and Mason 1990). However, there are other reasons for such a transition. Basically, one has to expect a transition when the cloud layer gets thin and turbulence gets strong enough to cause a separation between clouded updrafts and nonclouded downdrafts. The cloud layer gets thin when the boundary layer gets dried. The drying, in terms of relative humidity reduction, may be caused by heating of the layer at constant water content or by reduction of the total water content. Both processes may have various reasons, including surface heating, internal radiation heating, subsidence, entrainment of warm and dry air from above, or precipitation to the surface. The turbulent motion of updrafts and downdrafts within the convectively driven boundary layer plays an important role in these processes (Moeng and Schumann 1991), but the details are still to be investigated. Previous experimental observations (e.g., Finger and Wendling 1990; Paluch and Lenschow 1991) concentrated on the marine boundary layer. Much less information is available on clouds over land surface, where the drying by surface heating might be the most essential process.

The objective within the CLEOPATRA experiment was to investigate the transition from a solid to a broken cloud layer at top of the boundary layer over land by means of observations and modeling. The "Deutscher Wetterdienst" in particular used the experimental high-resolution version of the Europa Model (EM). This version has a mesh size of 0.125° instead of 0.5° as the EM.

d. Quantification of water vapor transports from soil and vegetation to the atmosphere in dependence on precipitation events and the state of vegetation for a given test area

The global energy and water cycle, which is one of the most important but still only qualitatively known climatic processes, needs more attention. The transport of water from precipitation into the soil structure, from ground into the vegetation, and from vegetation into the atmosphere needs to be known in dependence on meteorological conditions as precipitation events and precipitation-free episodes, as well as on the state of the vegetation itself. Measurements are needed in order to calibrate models of the water transportation within the complex and highly variable soil (Engmann et al. 1989; Schädler et al 1990; Eagleson 1978) and the evapotranspiration. These different models describing soil water fluxes and the evapotranspiration by the vegetation have been coupled by Sellers (1985) and Mauser (1991). The planetary boundary layer further links the water exchange with the free atmosphere.

The hypotheses to be proved were:

- The energy fluxes from a test area can be estimated in dependence on precipitation events, the duration of precipitation-free episodes, and the state of vegetation, soil moisture, and soil type.
- The in situ measurements, remote-sensing data (both microwave and optical) from aircraft, and spaceborne remote-sensing data can be used for upscaling and for the development of models that can cover larger areas.

e. Improvement and comparison of remote-sensing methods from ground, aircraft, and space for observing elements of the hydrological cycle

One important step in radar remote sensing of hydrometeors has been done during the last years by the installation of advanced polarimetric radar techniques (Bringi and Hendry 1990; Schroth et al. 1988). Different radar polarimetric parameters such as reflectivity, differential reflectivity, and linear and circular depolarization ratios, mostly in combination, are appropriate to distinguish between hydrometeor classes as cloud and rain droplets, heavy rain, graupel, and ice particles (Aydin et al. 1984; Meischner et al. 1991; Bringi et al. 1991).

More recently, time-series data evaluation gives the parameters as the differential propagation phase, the specific differential phase, and the cross-correlation coefficient. They make particle classifications more reliable and are used for correcting for propagation effects (Bringi et al. 1991; Bebbington et al. 1987; Sachidananda and Zrnić 1989; Schroth et al. 1990). Lidar depolarization for cloud particle characterization is a developing branch (Sassen and Petrilla 1986; Werner et al. 1992).

Remote sensing of the cloud-free atmosphere by lidar and by microwave radiometers are of importance for detection and monitoring of water vapor structures. Humidity structures at ground and vegetation indexing need combined use of remote optical as well as microwave measurements.

Remote-sensing methods for the atmosphere and land surface need cross calibration and in situ validation in order to proceed to operational applications.

PRIRODA ("Nature"), a module for earth observations to be connected with the Russian spacestation *MIR,* scheduled for launch in 1993, will have a complementing package of active and passive optical and radar instrumentation (Armand et al. 1991). CLEOPATRA was an opportunity for testing PRIRODA instrumentation and evaluation methods.

The goals were:

- quantification of hydrometeor detection by radar polarimetry, lidar polarization, and in situ measurements and estimation of propagation effects; and
- cross calibration of in situ and remote-sensing methods from ground, aircraft, and satellites detecting hydrometeors, water vapor fluxes, soil moisture, and vegetation index.

f. Quantification of the impact of weather elements on satellite communication links

Satellite communication links, operating at frequency bands above 20 GHz, are seriously affected due to scattering by atmospheric hydrometeors. These effects have to be taken into account for link estimations in the planning and design stages, as well as under operational conditions.

Future aircraft radar guidance for traffic control, detection, and discrimination of targets under adverse weather conditions require knowledge of dispersive polarimetric signatures of atmospheric precipitation. Objectives were:

- to provide correlations between degradations of satellite communication signals above 20 GHz and characteristic precipitation events; and
- development of atmospheric high-frequency models for satellite communication system planning and design.

3. Strategy

The measurement site is located in the pre-Alpine area, west of Munich (Fig. 1). The test site is hilly, with a heterogeneous land use, average-sized fields, and a good infrastructure. There were ground-based observation systems, operational during the period from 11 May to 31 July. The aircraft operated from Oberpfaffenhofen. We had two periods of special observations: 18 May–5 June and 13–31 July. During these periods, most observation systems were in operation.

Sixteen flight missions coordinated with ground-based and remote observations, depending on weather conditions, have been defined. Examples are flights with three aircraft staggered in altitude to trace chemical reactions and scavenging processes in stratiform and convective clouds. Precipitation sampling at ground for later chemical analysis is coordinated with these flights. Flight missions for determination of cloud dynamical processes such as mass budgets, mixing with environmental air, and cloud dissipation are complemented by radar Doppler and polarization measurements. Flights for airborne remote sensing of soil moisture, vegetation index, and humidity transports to the atmosphere link the ground-based in situ measurements to satellite observations. These flights were performed regularly for a special test site within the overall site covering the growing season. They were further coordinated with *ERS-1* overflights and tuned to precipitation events.

Another category of flight measurements was dedicated to improve the interpretation of radar polarimetric and lidar polarization measurements of hydrometeors by comparison with in situ cloud physical measurements.

For the coordination of measurements and for flight planning, an operation center was established during CLEOPATRA at the DLR Institute of Atmospheric Physics at Oberpfaffenhofen. Weather forecasts were provided on the basis of actual information from Deutscher Wetterdienst, Meteosat, and NOAA data received at DLR and project radar observations. The radar observations further supported in-flight decisions. Mission planning for the following day was performed on the basis of weather forecast and system status by a missions steering group. A data exchange agreement ensured the availability of first quality-controlled data by the end of October 1992.

4. Instrumentation

The observational equipment included the following.

a. 10 research aircraft

- The two-engine jet *Falcon* (DLR) was equipped with alternative instrumentation packages. They included standard meteorological equipment, a 5-hole probe for turbulence measurements, cloud-physics instrumentation including two PMS (particle measuring systems) 2D probes and a particle impactor probe, a polarization diversity microlidar, a Daedalus scanner, a DIAL (differential-absorption lidar) system for water vapor and ozone, radiation measurement probes, in situ ozone probe, humidity measurement device for low humidities, and a chaff-release facility.

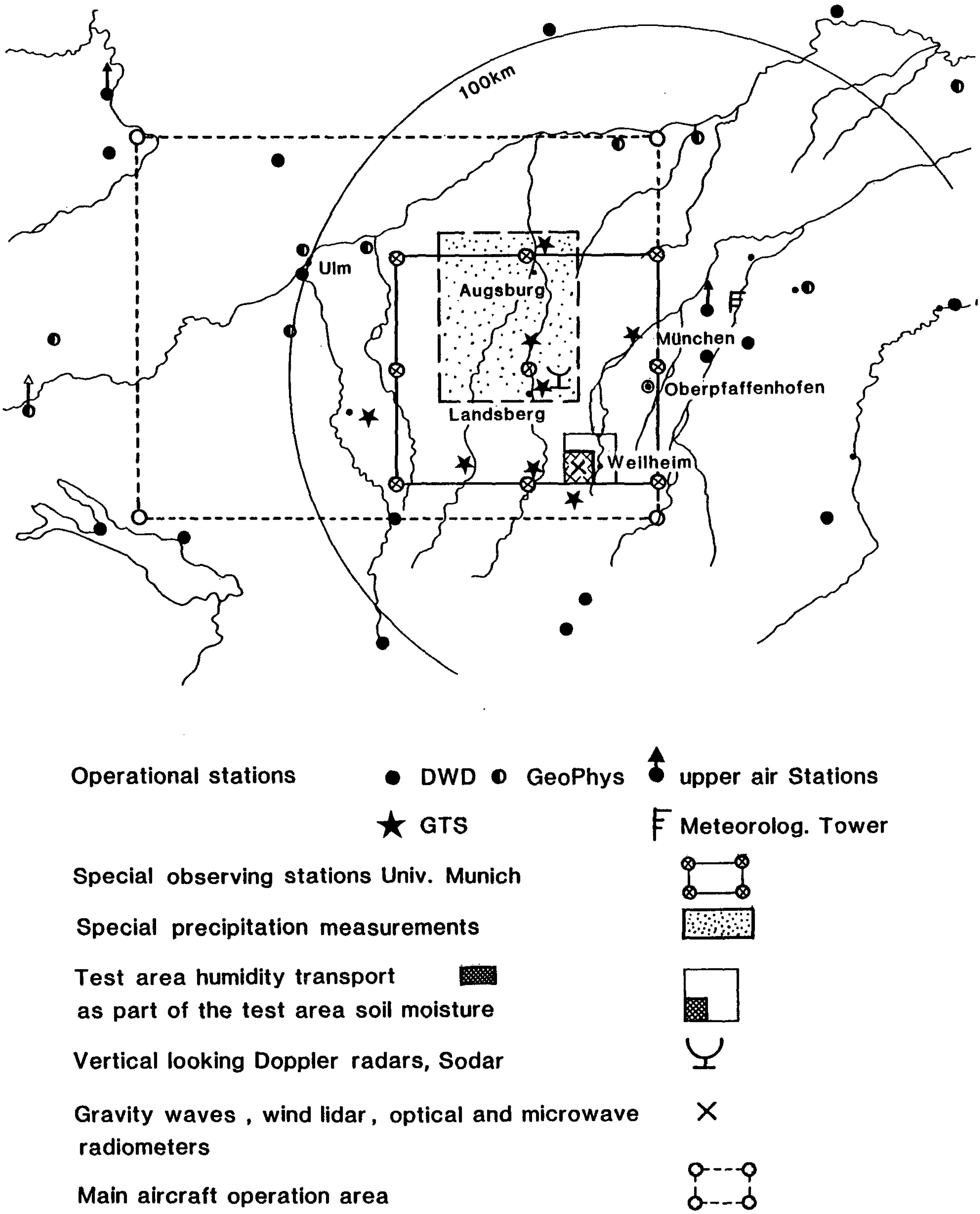

FIG. 1. Test site of CLEOPATRA, showing locations of ground-based observation systems. DWD: Deutscher Wetterdienst (German meteorological service); GeoPhys: Geophysikalischer Beratungsdienst (Military meteorological service); GTS: Link to the global telecommunication system of meteorological services.

- A Piper Chieftain (Center for Environmental Research, Frankfurt) was equipped with standard meteorological instrumentation, cloud physics instrumentation, cloud water sampling device, aerosol sampling, particle sampling by filter enrichment, and trace gas sampling (SO_2, NO_x, O_3, H_2O_2, SO_2, H–CHO).
- A Dornier DO 228 (DLR) was equipped with standard meteorological instrumentation and trace gas sampling devices for SO_2, NO_x, ozone, particle sampling, and CCN (cloud condensation nuclei) counter. This aircraft was further equipped with upward- (0.8 and 1.35 cm) and downward- (21 and 27 cm) looking microwave radiometers from the Institute of Radio Engineering and Electronics (IRE), Moscow.
- A Dornier DO 228 (DLR) was equipped mainly with synthetic aperture radar (SAR) for vegetation and soil moisture mapping. Alternative instrumentation is an optical scanner.
- A Dornier DO 128 (Technical University Braunschweig and University Mainz) was equipped with standard meteorological instrumentation. The measurements include wind, water vapor mixing ratio, and collection of cloud water.
- A Cessna 207 (DLR) was used for profiling for altitudes up to about 4000 m AGL.
- Three powered gliders (DLR) provided meteorological standard parameters and turbulence parameters for flux measurements.
- A Jljuschin-18 (IRE) with some PRIRODA instrumentation was used.

b. Four radar systems

- A C-band polarization Doppler radar (POLDIRAD) at Oberpfaffenhofen (DLR)
- A C-band Doppler radar at Hohenpeissenberg (Deut-scher Wetterdienst)
- A vertical-looking X-band Doppler radar (ETH Zürich)
- A vertical-looking 1.23-GHz FM-CW Doppler radar (University Hamburg)

c. Ground observational network

- 15 micrometeorological stations, including one sounding system (University Munich)
- The observational network from Deutscher Wetterdienst including soundings and precipitation measurements
- Precipitation measurement networks from various local agencies
- Different microwave radiometers (DLR, University Munich, IRE Moscow)
- Radiometer/beacon receiver station (DLR)
- Raingages and disdrometers (DLR, universities)
- Soil moisture and vegetation indexing instrumentation (University Munich)
- Pressure network for detecting gravity waves (DLR)
- Acoustic sounding systems (University Oldenburg)
- Doppler wind lidar (DLR)
- Mobile stations for micrometeorological, precipitation, analytical, and radiation budget measurements (University Bonn, Technical University Darmstadt, DLR, DWD)

These systems were located in the measurement area west from Oberpfaffenhofen such that coordinated aircraft operations could be performed within a 100-km distance from the radars (see Fig. 1).

d. Satellites

Data for scientific applications and missions planning are used from

- Meteosat
- *NOAA-11*
- *Landsat-5*
- *MOS-1*
- *Olympus, Kopernikus*
- *Almaz*

5. Observational results

a. Meteorological conditions

The observation period of CLEOPATRA (11 May–31 July 1992) was rather unusual with respect to the weather. Generally, it was too warm and too dry compared to the long-term mean. The three-month average temperature in Munich (17.2°C) exceeded its climatic value by +2.3 K, whereas the amount of precipitation (94 mm) reached only 25% of its normal level. The sum of sunshine hours (694 h) came up to 106% of the long-term mean. The monthly values are presented in Table 1.

This extreme situation, especially the precipitation deficit, was caused by several blocking situations, which over eastern and northern Europe finally resulted in a pressure excess of up to 5 hPa. Hence, this year easterly winds and dry continental air were observed more frequently than usual in our area.

In June and July the southern and western parts of the experimental area were hit by thunderstorms more frequently than the Munich area. Thus, the precipitation sum reached its normal level near the Alps and even exceeded it in the area west of the river Lech.

Time–height cross sections of wind, temperature,

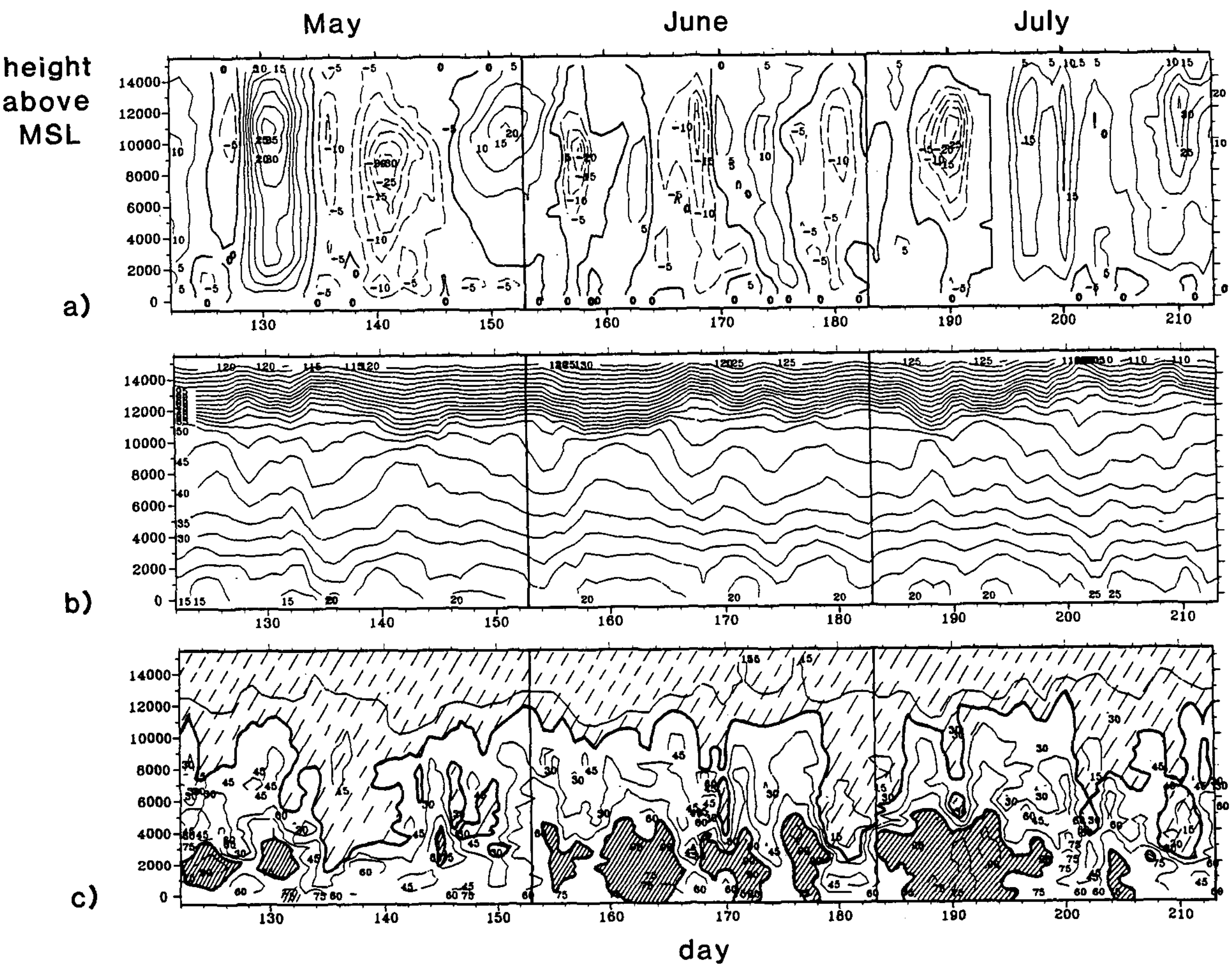

FIG. 2. Time–height cross sections of the west–east component of the wind in m s^{-1} (a), the potential temperature in °C (b), and the relative humidity in percent (c) over Munich. Plotted are daily mean values on the base of the 0000 and 1200 UTC radiosonde data.

and humidity were derived from the Munich radiosonde data. They are presented in Fig. 2. The relative frequent periods with easterly winds are remarkable. They often coincide with high potential temperatures and low relative humidity. Several periods with high relative humidity (more than 75%) occurred in June and in the first half of July. They indicate larger amounts of clouds.

The static and conditional stability of the air was measured by the potential and equivalent-potential temperature difference between the 500- and 850-hPa level (Fig. 3b), again derived from Munich radio soundings. Periods of strongly reduced stability were found in May, at the beginning of June and July, and in the second half of July. With the exception of May, where too little precipitable water was available, these

TABLE 1. Monthly values from the CLEOPATRA observation period.

	Temperature		Precipitation		Sunshine	
	1992	Deviation from climate	1992	Percentage from climate	1992	Percentage from climate
May	+14.9°C	+2.9 K	8 mm	8%	284 h	138%
June	+17.0°C	+1.5 K	42 mm	31%	179 h	84%
July	+19.6°C	+2.3 K	44 mm	34%	231 h	99%

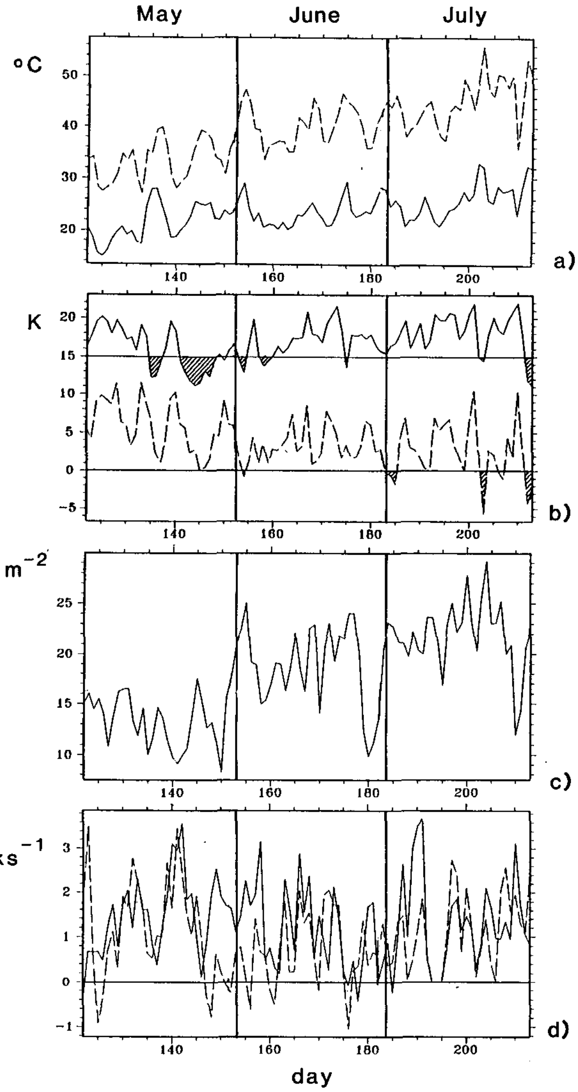

FIG. 3. Temporal variation of the potential temperature (plate a, solid) and equivalent potential temperature (plate a, broken) at 850 hPa; the difference between 500 and 850 hPa of the potential temperature (plate b, solid) and the equivalent potential temperature (plate b, broken); the total precipitable water content in the air (plate c); and the vertical wind shear between 300 and 700 hPa (plate d, solid) and between 500 and 850 hPa (plate d, broken) over Munich. Plotted are daily mean values based on the 0000 and 1200 UTC radiosonde data.

periods mark the greatest thunderstorm activity during CLEOPATRA.

A short period of strong westerly winds at the beginning of the experiment, 11–12 May, was followed by a more or less stationary high pressure situation for the rest of the month. Initially, warm continental air from the southeast was transported to southern Bavaria, and then, as on 17 May, cooler but still dry air came in from northeast. Although the air was temporarily less stable, convective precipitation could not develop due to lack of precipitable water. Toward the end of May, warmer and moister air arrived again; however, only at the beginning of June did the air become moist and unstable enough to allow thunderstorms.

From 6 to 13 June, the approach of an upper-air low pressure system caused moderate temperatures and local showers or rain. After a short warming period, cool air of polar origin arrived from the north along the eastern flank of an eastern Atlantic high. From 18 to 25 June, the weather was mostly cool with some thunderstorms on the 24th and 25th. From 26 June to the end of the month, anticyclonic influence was dominant, with high temperatures and no rain.

During the first week of July, some precipitation was associated with the passage of fronts. After a few dry days from 8 to 10 July, a cold front produced precipitation on 11 July. This was the only CLEOPATRA day with several hours of uniform rain during daytime in the experimental area. The following days had changing weather, with some showers and moderate temperatures. From 14 to 21 July, fair weather without precipitation was dominant. After a short period of cold-front passages and some showers, the anticyclonic influence again became dominant. It lasted until the end of the CLEOPATRA experiment.

b. Objectives and measurement results

A number of multicell thunderstorms, three cases of squall-line systems, and one case of a supercell structure were observed. They are well documented by the ground-based systems, especially by detailed measurements taken with the multiparameter radar, which concerns cloud microphysics and cloud dynamics. An overview is given in Fig. 4. A rather simple classification of the convective cells according to single cells, multicells, and supercells was adopted in order to somehow reflect the degree of organization of the storms. During most of the thunderstorm days, the cells did not overcome the single-cell stage. Multicel-

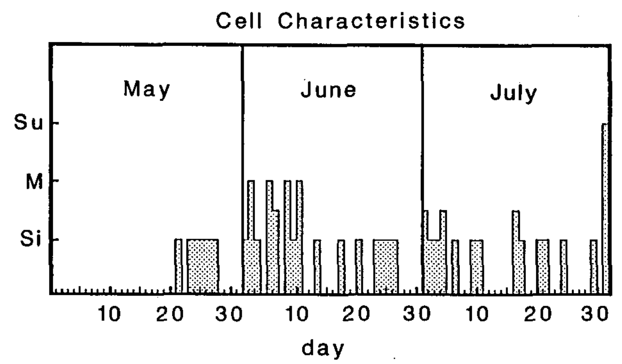

FIG. 4. Cell characteristic during the observational period. The storms were classified as single cells (Si), multicells (M), and supercells (Su).

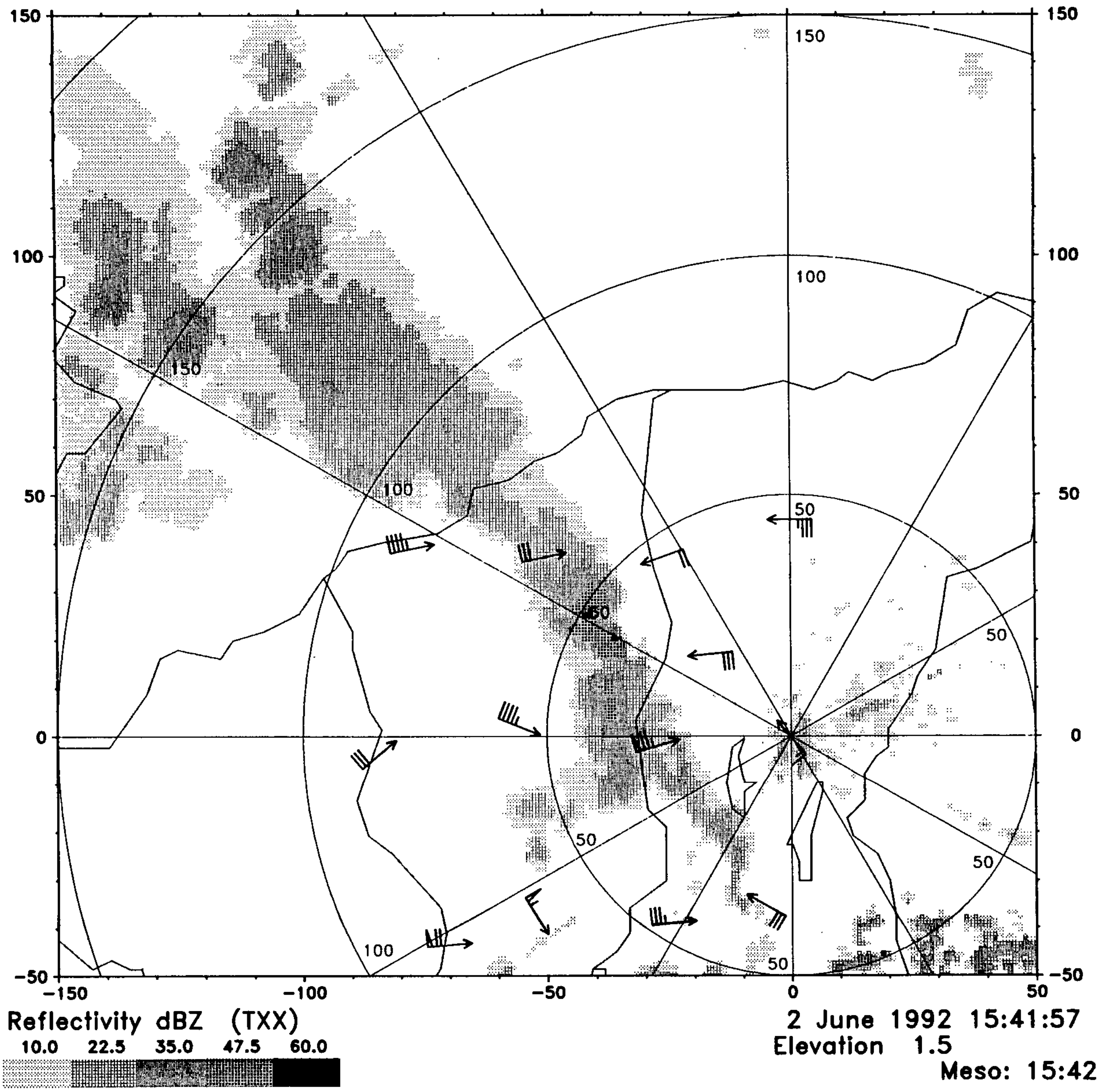

FIG. 5. The radar reflectivity structure of the squall line of 2 June 1992 and the preliminary wind field as derived from measurements of the micrometeorological stations of the University Munich (courtesy of Hans Schroers).

lular characteristics were reached at 4 days, as well as some intermediate types of developments. One supercell case (31 July) was observed during the experimental period. The observations of the squall-line cases further include frequent radio sounding and dynamical measurements within the PBL, with three powered gliders in front of the line and to some extent behind the line, too.

An example is shown in Fig. 5. A general finding is that convective systems show a higher degree of organization if they are connected to general westerly airflow—possibly because of more clearly developed wind profiles. No squall-line system approached from the east. Further, several hailfalls were positively correlated with the degree of organization of the storms. The influence of the Alps on an eastward-moving line disturbance is documented by an acceleration of the southern part near to the mountains.

Gravity waves were clearly observed by the newly installed high-sensitivity pressure sensors in connection with convective activities. At least one gust front originating from a thunderstorm outflow was clearly identified as the cause of gravity waves propagating ahead of the system.

Well-coordinated chemical measurements were performed using three aircrafts—the Piper Chieftain, a Dornier DO 228, and the Dornier DO 128—in convective as well as in stratiform clouds. This to our knowledge was the first time that cloud physics and chemical processes were simultaneously observed in time and space. The most interesting cases were found at the beginning of June. On 1 and 2 June, cumulus clouds were sampled at different heights above cloud base and below by the three aircraft. On 2 June the same cloud was sampled by the three planes in different altitudes. For one developing stratiform case on 3 July, data were collected before and during intensifying precipitation formation. Three levels within and one below the cloud layer were flown by the three aircraft in staggered pattern perpendicular to the direction of the approaching system.

Beside meteorological data, these measurements include liquid water content and cloud-droplet spectra, aerosol particle spectra, NO_x, SO_2, O_3, H_2O_2, and H-CHO in the gas phase, as well as filter enrichments for S(VI), anions, cations, and metal ions. The sampled cloud water is analyzed for H_2O_2, S(IV), S(VI), anions, cations, metal ions, Fe II/Fe III, organic acids, organic peroxides, pH, and conductivity.

On-ground coordinated collection and standard and cryogenic sampling of precipitation drops allow for chemical analysis as a function of drop size. These include H^+, CL^-, SO_4^{2-}, NO_3^-, HCO_2^-, $CH_3CO_2^-$, NH_4^+, K^+, Na^+, Ca^{2+}, Mg^{2+}, and pH. A significant difference in trace gas content of cloud water and rainwater is already documented (Bächmann et al., University Darmstadt, 1992, personal communication).

Broken stratocumulus cloud layers at the top of the boundary layer did not appear during the field phase; nevertheless, the measurement strategy was tested.

All ground-based observation systems operated continuously during the field phase. The 15 micrometeorological stations of the University of Munich gave a very good insight about the dynamics of convective systems. The wind field shown in Fig. 5 is a preliminary result.

For the "test-area soil moisture," four energy-balance stations for the measurement of water vapor and energy fluxes were installed over three different surface types: corn, wheat, and grassland. On the grassland, care was taken to select one plot with a high and one with a low groundwater table. Meteorological profile measurements of the first 10 m of the atmospheric boundary layer were integrated to a temporal resolution of 0.5 h. In parallel to these energy-balance measurements, and at the same locations, soil moisture was continuously recorded at three different depths using tensionmeters and gypsum blocks. The measurements showed considerable differences in the soil moisture and the movement of the wetting front after rainfall events for the four different locations.

The meteorological measurements were backed by weekly measurements of plant parameters for the land uses in the test area. The following parameters were determined: phenology, plant height, biomass (wet and dry), leaf-area index, stomatal conductance, and CO_2 fixation. Daily courses of the stomatal conductance were recorded, as was the CO_2 fixation on selected days. Flights across the test area were performed with X-band, C-band, and L-band SAR with different polarizations in a prefixed sequence of 3 to 5 days during the two periods of intense observations. Both wet and dry periods were covered. Some of these flights were performed simultaneously with water vapor measurements by the airborne DIAL and with airborne microwave radiometers (0.8-, 1.35-, 21-, and 27-cm wavelength) of IRE Moscow. This especially was done in coordination with the *ERS-1* overflight on 1 June so that the linked soil surface–boundary layer–free atmosphere can be investigated by different methods. A special flight with the Russian research aircraft *Jlynshin-18*, equipped with PRIRODA instrumentation, was performed on 30 July with clear-air conditions at the test site. These measurements include S-band SAR, scanning multichannel microwave radiometers (0.3, 0.8, 1.35, and 2.25 cm), optical multispectral scanner, microwave radiometers (2.25 and 6 cm), and different cameras. This flight was coordinated with X-, C-, and L-band SAR measurements for different polarizations by the DLR plane. The Russian S-band radar satellite *Almaz* on that day was operated so as to view the test site with a nadir angle of 39.47°. In parallel to all flights, the soil moisture of the top 5 cm was determined gravimetrically.

For the "test-area humidity transport" of approximately 100 km², the land use of each field was determined and is currently being integrated in a geographical information system. With these data, a complete set of measurements for spatially inhomogeneous modeling of surface energy fluxes, as well as for the validation of these models in a small-scale area, is now available.

The stratiform precipitation case of 11 July showed a well-developed bright band for the different radar polarimetric parameters. Detailed measurements with POLDIRAD were performed together with in situ measurements by the Falcon including PMS 2D probes and with the vertical-looking 1.23-GHz FM-CW Doppler radar. Figure 6 shows first results including images of a PMS 2D-C probe from different heights. The peaks of ZYY, ZDX, and ZDR occur clearly at different heights, which is supported by the visual appearance of the particles. The fall velocity increases until all aggregates are collapsed to raindrops. This excellent

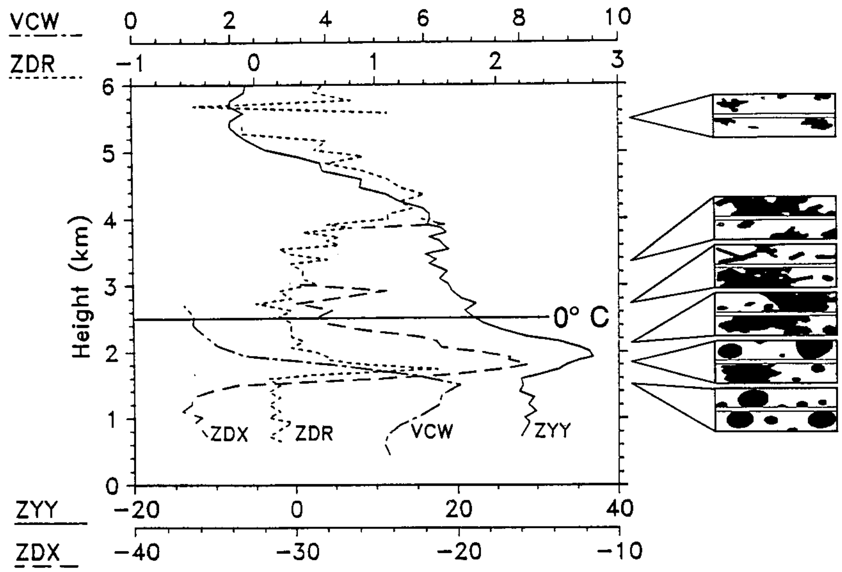

FIG. 6. Vertical profiles of the horizontal reflectivity ZYY in dBZ, differential reflectivity ZDR in dB, linear depolarization ratio ZDX in dB, and vertical fall velocity VCW in m s^{-1}, over Penzing on 11 July 1992 at 1110 UTC. ZYY, ZDR, and ZDX were measured by the polarimetric Doppler radar Oberpfaffenhofen—27 km from Penzing—and VCW was measured by the vertical-pointing Doppler radar of the University Hamburg (courtesy of Carolin Richter). The particle images at the right side indicate the measurements with a PMS 2D-C probe by the DLR Falcon at six different heights.

case will be used to apply the newly developed polarimetric radar methods for identifying different hydrometeor types, study the melting process, and compare rain-rate estimations. These were performed by ground measurements, disdrometers, reflectivity radar, polarimetric radar, both vertical-measuring Doppler radars, and microwave radiometers. Sufficient material for comparison has been gathered.

Additionally, frequent coordinated measurements were taken in the clear atmosphere by Doppler radar, polarimetric radar, water vapor DIAL, radiosounding, and aircraft in situ measurements in order to investigate the stratification of the atmosphere including the water vapor distribution. These data, together with satellite observations and the ground-based measurements, will allow the water exchange between soil and atmosphere to be estimated and methods to be compared.

The polarization DLR-microlidar was flown for the first time. For the campaign a new laser was used with a unique capability of varying the output power. Therefore, it was possible to measure both within clouds and from above during the same flight. Qualitative comparison of lidar data with particle probe measurements showed that it is possible to distinguish ice clouds (cirrus) from liquid water and mixed-phase clouds immediately via the four-channel signals; the application of the mathematical methods developed in Oppel et al. (1989) enables a quantitative analysis of the signals to determine microphysical parameters even under conditions of strong multiple scattering.

Interesting free-field sound-propagation measurements were carried out by a group from the University of Oldenburg in order to test acoustic remote-sensing techniques for the measurement of meteorological boundary-layer parameters. Comparing a theoretical model of sound propagation in a layered atmosphere with measured data, it is possible to determine wind and temperature profiles. The height depends on the propagation distance and was about 50 m in this case. Moreover, the acoustical properties—the reflection coefficient and the acoustic impedance—of ground was measured. The objective of these measurements is to determine soil parameters (e.g., porosity or water content) in situ and noninvasively. These measurements were carried out on the "test-area soil moisture" in order to compare data.

Along the path of the *Olympus* satellite, a total of 40 h of stratiform, as well as convective precipitation events—some including hail—were well documented by the polarimetric radar measurements, in situ aircraft measurements, including microphysics, and by distrometer and 19-GHz radiometer measurements at the ground. They will be used to explain the degradation of satellite communication signals as measured simultaneously by the *Olympus* beacon signal at 19.77 GHz.

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equipped with sophisticated instrumentation, and a ground-based system enabled size-dependent chemical analysis of single raindrops. Members of the DFG Schwerpunkt "Physikalische Methoden der Fernerkundung von Atmosphäre und Hydrosphäre" together with DLR used and compared remote-sensing methods, and members of the DFG Schwerpunkt "Regionalisierung in der Hydrologie" investigated the water transports in a regional scale. The contribution of the Institute of Radioengineering and Electronics, Moscow, with airborne and ground-based microwave radiometers, was funded by DARA, Deutsche Agentur für Raumfahrtangelegenheiten GmbH. Such radiometers will be flown on PRIRODA, a module for remote sensing of the earth, to be docked to the Russian space station *MIR* in 1993 or 1994.

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References

Ahr, M., A. I. Flossmann, and H. R. Pruppacher, 1989: On the effect of the chemical composition of atmospheric aerosol particles on nucleation scavenging and the formation of a cloud interstitial aerosol. *J. Atmos. Chem.*, **9**, 465–478.

Aydin, K., T. A. Seliga, and V. N. Bringi, 1984: Differential radar scattering properties of model hail and mixed phase hydrometeors. *Radio Sci.*, **19**, 58–66.

Armand, N. A., 1991: Orbital station "MIR," complex of remote sensing of the earth "PRIRODA", Scientific Program. Institute of Radioengineering and Electronics of the USSR Academy of Sciences, Moscow.

Bebbington, D. H. O., R. McGuinness, and A. R. Holt, 1987: Correction of propagation effects in S-band circular polarization-diversity radars. *IEE Proc. H: Microwaves, Antennas and Propag.*, **134**(5), 431–437.

Bringi, V. N., and A. Hendry, 1990: Technology of polarization diversity radars for meteorology. *Radar in Meteorology*, D. Atlas, Ed., Amer. Meteor. Soc., 153–190.

——, V. Chandrasekar, P. Meischner, J. Hubbert, and Y. Golestani, 1991: Polarimetric radar signatures of precipitation at S- and C-bands. *IEE Proc. F*, **138**(2), 109–119.

Deardorff, J. W., 1980: Cloud-top entrainment instability. *J. Atmos. Sci.*, **37**, 131–147.

Eagleson, P. S., 1978: Climate, soil and vegetation. *Water Resour. Res.*, **14**, 705–776.

Engmann, E. T., G. Augus, W. Kustas, 1989: Relationships between the hydrologic balance of a small watershed and remotely sensed soil moisture. *Remote Sensing and Large-Scale Global Processes*, A. Rango, Ed., IAHS Public. No. 186, 75–86.

Finger, J. E., and P. Wendling, 1990: Turbulence structure of arctic stratus clouds derived from measurements and calculations. *J. Atmos. Sci.*, **47**, 1351–1373.

Flossmann, A. I., 1991: The scavenging of two different types of marine aerosol particles, calculated using a two-dimensional detailed cloud model. *Tellus*, **43B**, 301–321.

——, and H. R. Pruppacher, 1988: A theoretical study of the wet removal of atmospheric pollutants. Part III. *J. Atmos. Sci.*, **45**, 1857–1871.

——, Hall, W. D., and H. R. Pruppacher, 1985: A theoretical study of the wet removal of atmospheric pollutants. Part I. *J. Atmos. Sci.*, **42**, 583–606.

——, Pruppacher, H. R., and J. H. Topalian, 1987: A theoretical study of the wet removal of atmospheric pollutants. Part II. *J. Atmos. Sci.*, **44**, 2912–2923.

Hauf, T., and T. L. Clark, 1989: Three-dimensional numerical experiments on convectively forced internal gravity waves. *Quart. J. Roy. Meteor. Soc.*, **115**, 309–333.

Koch, S. E., and R. E. Golus, 1988: A mesoscale gravity-wave event observed during CCOPE. Part I: Multiscale statistical analysis of wave characteristics. *Mon. Wea. Rev.*, **116**, 2527–2544.

Krämer, M., and L. Schütz, 1988: Insoluble particles in hydrometeors. Preprints, *10th Intl. Cloud Phys. Conf.* Bad Homburg, 238–240.

Kuo, H., and W. H. Schubert, 1988: Stability of cloud-topped boundary layers. *Quart. J. Roy. Meteor. Soc.*, **114**, 887–916.

MacVean, M. K., and P. J. Mason, 1990: Cloud-top entrainment instability through small-scale mixing and its parameterization in numerical models. *J. Atmos. Sci.*, **47**, 1012–1030.

Mauser, W., 1991: The integration of remote sensing data in a GIS to model spatial evapotranspiration and soil moisture distribution. *Proc. ESIS'92*, Munich, 1140–1149.

Meischner, P., V. N. Bringi, D. Heimann, and H. Höller, 1991: A squall line in southern Germany: Kinematics and precipitation formation as deduced by advanced polarimetric and Doppler radar measurements. *Mon. Wea. Rev.*, **119**, 678–701.

Moeng, C.-H., and U. Schumann, 1991: Composite structure of plumes in stratus-topped boundary layers. *J. Atmos. Sci.*, **48**, 2280–2291.

Oppel, U. G., A. Findling, W. Krichbaumer, S. Krieglmeier, and M. Noormohammadian, 1989: A stochastic model for the calculation of multiply scattered lidar returns. DLR-Research Report 89-36, 219 pp.

Paluch, I. R., and D. H. Lenschow, 1991: Stratiform cloud formation in the marine boundary layer. *J. Atmos. Sci.*, **48**, 2141–2158.

Pruppacher, H. R., 1986: The role of cloud physics in atmospheric multiphase systems: Ten basic statements. *NATO ASI Series, Vol G 6*, Springer-Verlag Berlin, 133–190.

Randall, D. A., 1980: Conditional instability of the first kind upside down. *J. Atmos. Sci.*, **37**, 125–130.

Sachidananda, M., and Zrnić, D. S., 1989: Efficient processing of alternately polarized radar signals. *J. Atmos. Oceanic Technol.*, **6**, 173–181.

Sassen, K., and Petrilla, R. L., 1986: Lidar depolarization from multiple scattering in marine stratus clouds. *Appl. Optics*, **25**, 1450–1459.

Schädler, G., N. Kalthoff, and F. Fiedler, 1990: Validation of a model for heat, mass and momentum exchange over vegetated surfaces using LOTREX-10E/HIBE88 Data. *Beitr. Phys. Atmosph.*, **63**, 85–100.

Schroth, A. C., M. S. Chandra, and P. F. Meischner, 1988: A C-band coherent polarimetric radar for propagation and cloud physics research. *J. Atmos. Oceanic Technol.*, **5**, 803–822.

——, K. Tragl, E. Lüneburg, and M. Chandra, 1990: Polarimetric signatures of extended meterological targets derived with the DLR radar. *SPIE Vol. 1317, Polarimetry: Radar, Infrared, Visible, Ultraviolet and X-Ray.*

Schütz, L., and M. Krämer, 1987: Rainwater composition over rural areas with special emphasis on the size distribution of insoluble particulate matter. *J. Atmos. Chem.*, **5**, 173–184.

Sellers, P. J., 1987: Canopy reflectance, photosynthesis, and transpiration. II: The role of biophysics in the linearity of their interdependence. *Remote Sens. Environ. Sci.*, **6**, 1335–1372.

Weisman, M. L., and J. B. Klemp, 1982: The dependence of numerically simulated convective storms on vertical wind shear and buoyancy. *Mon. Wea. Rev.*, **110**, 504–520.

Werner, Ch., J. Streicher, H. Herrmann, H. G. Dahn, 1992: Multiple scattering lidar experiments. *Optic. Engin.*, **3**, 173–174.

WMO, 1992: Global Energy and Water Cycle Experiment (GEWEX). Report of the fourth session of the JSC scientific steering group for GEWEX, Tokyo, Japan, WMO/TD-No. 490.